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Development and Implementation of Generalized Mathematical modeling of HPO Induction motor Drive Using MATLAB/Simulink

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Abstract: This paper presents a generalized model of Induction motor with phase number (n) greater than 3. In general, the machines with phase number greater than three posses several advantages such as less torque ripple, fault tolerant capability, phase redundancy, high torque density, stability, high efficiency and lower current ripple. There is a possibility to increase the power/torque per rms ampere for the machines with the phase number more than three for the same volume of the machine. In this paper, a generalized model the high phase order induction machine drive is developed in MATLAB/Simulink using basic built in blocks of Simulink. This model is fed from pure sinusoidal source. This model is tested for the phase numbers 5,7,9, 12, 15 and 18. The simulation results are observed for varying loading conditions. The transient response of the multi-phase induction motors are also given for different phase numbers of the High Phase Order induction machine.
Keywords: Clarke's transformation, Multi-phase induction motor (HPO), d-q axes model.

I. INTRODUCTION

The three phase machines are mostly used as variable-speed electrical drives. As compared to conventional three phase induction machines, the high phase order machines posses the following advantages [1], [2].

1. Improved reliability and increased fault tolerance;
2. Greater efficiency;
3. Higher torque density and reduced torque ripple;
4. Lower per phase power handling requirements;
5. Enhanced modularity;
6. Improved noise characteristic etc.

The high phase order drive is likely to remain limited to specialized applications where high reliability is demanded such as electrical/hybrid vehicles, aerospace applications, ship propulsion, and high power application where a combination of several solid state devices form leg of the drive. Recently, the high phase order system applications include high torque low speed brush less machines applied to electric vehicle propulsion [3], permanent magnet motor drives for ship propulsion [4], permanent motor with low torque pulsation [5] and a single phase inverter supplied series connected two motor drives [6].

To obtain the general model of a high phase order Induction machine, the general theory of electrical machines provides sufficient means. It is sufficient for dealing with mathematical representation of an Induction machine with an arbitrary number of phases on both stator and rotor. The HPO induction machine can be designed with sinusoidal distributed winding or with concentric winding. The modeling is available at general level in [7].

It is possible to house the HPO Induction machine with the same size as that of the three phase induction machine. Hence current per phase is reduced. To develop a general model, winding displacement is taken into consideration. It is not necessary the winding displacement is symmetrical. The derived voltage equations in phase variable form and dqo axes transformation of unsymmetrical displacement windings of a multiphase induction machines has been reported in [8].

Reference [9] deals with the experimental tests carried out on a small Induction machines connected to six phases and to nine phases. It includes torque measurements over entire speed range and load tests with balanced source with one phase open.

A detailed modeling of a high phase order induction machine, including the high spatial harmonics of a five phase induction machine has been investigated in [12]. It contains transformation using real or complex matrix transformations of machine phase variables resulting in corresponding real or space vector models of the multiphase machine.

A Vectorial modeling of multiphase induction machine is discussed in [10, 11]. It represents a kind of generalization of space vector theory, applicable to all AC machines. Induction motor performance as a function of Phase number is discussed in [2]. It gives the analytical and experimental comparison. In this a method of generalized complex harmonic analysis is used to model the multiphase machine, including torque calculation.

A comparative study between the measured instantaneous torque of the both three phase and 6 phase six step voltage source fed Induction machines is studied in [12]. It gives the advantages of the six phase system over the three phase system in eliminating the sixth harmonic dominant torque ripple. Reference [13], discusses how stator losses are attenuated by as much as 8.5% with the phase number more than 3. In addition, a general expression for the harmonic fields produced when a machine having any phase number excited from a PWM inverter derived and the sources of torque pulsation are identified.

The strategies for the fault tolerant current control of a 5-phase Permanent magnet motor are discussed in [14]. The analysis covers both the open circuit of one and two phases and short circuit at the machine terminal of one phase. An analytical model has been used to investigate the properties of each post fault strategy.

Variable-speed applications of multiphase electrical machines fed from multiphase voltage source inverter are addressed in [15]. It also addressed the application of multiphase machines in electrical energy generation.

Reference [16] addresses a technological survey on multi-phase Induction machine drives. It discusses the characteristics of high phase order harmonic fields produced by the fundamental frequency excitation in multiphase machines for common phase numbers. It is also discussed the reduction of stator joule loss with the increase in phase number more than three. It also addresses the speed control techniques of multiphase Induction machine drives.

Independent flux and torque control of AC machines is possible with the principle of vector control It controls using two stator d-q axes currents. There exists an additional degree of freedom with the phase number more than three i.e., enhanced overall torque production through injection of higher stator current harmonics in High Phase order Induction machine. Modeling of multiphase machines with unbalanced structure is discussed in [16]. It also discusses the Field Oriented controlling of the HPO machine transforming the unbalance stationary frame to synchronous frame. Modeling of machines leads to an insight into the electro-mechanical and electrical transients. Generalized d-q models for high phase order machine is not available in common simulation packages. This paper focuses on the development of flexible simulation model of generalized n-phase machine model of induction motor. A simple approach is proposed to utilize the built in blocks of MATLAB/Simulation software. An attempt is made in this paper to obtain the various simulation results for high phase order Induction machines under different loading conditions. It is fed from pure sinusoidal supply with symmetrically distributed winding [17].

II. MATHEMATICAL MODELING OF N-PHASE INDUCTION MOTOR

The particular cases of well-known n-phase machine are the well-known Space vector and d-q axes models of three phase machines only. Since the phase-variable model of a physical multiphase machine gets transformed using a mathematical transformation, the number of variables before and after transformation must remain the same. This means that n-phase machine will have n new stator current (stator voltage, stator flux) components after the transformation. An n-phase symmetrical induction machine, such that the spatial displacement between any two consecutive stator phase equals $\alpha=2\pi/n$, is considered. It is assumed that the windings are sinusoidal distributed, so that all higher spatial harmonics of the magneto-motive force can be neglected.

The phase number n can be either odd or even. It is assumed that, regardless of the phase number, windings are connected in star with a single neutral point. The machine model in original form is transformed using decoupling (Clarke's) transformation matrix [3], which replaces the original sets of n variables with new sets of n variables. Decoupling transformation matrix for an arbitrary phase number n can be given in power invariant real or complex matrix transformations, resulting in corresponding real or space vector models of the multiphase machine. Decoupling transformation matrix for an arbitrary phase number n can be given in power invariant form with Fig. 1 where $\alpha=2\pi/n$. The first two rows of the matrix in Fig. 1 define variables that will lead to fundamental flux and torque production (α–β components; stator to rotor coupling appears only in the equations for α–β components). The last two rows define the two zero sequence components and the last row of the transformation matrix in Fig. 1 is omitted for all odd phase numbers n. In between, there are x–y components. Equations for pairs of x–y components are completely decoupled from all the other components and stator to rotor coupling does not appear either [3]. These components do not contribute to torque production when sinusoidal distribution of the flux around the air-gap is assumed. A zero-sequence component does not exist in any star-connected multiphase system without neutral conductor for odd phase numbers, while only zero components can exist if the phase number is even. Since rotor winding is short-circuited, both neither x–y nor zero-sequence components can exist, and one only needs to consider further on α–β equations of the rotor winding. As stator to rotor coupling takes place only in α–β equations, rotational transformation is applied only to these two pairs of equations. Its form is similar to a three-phase machine. Assuming that the machine equations are transformed into an arbitrary frame of reference rotating at angular speed ω_e, the model of an n-phase induction machine with sinusoidal winding distribution is given with

$$\begin{bmatrix} V_d \\ V_q \\ V_{x1} \\ V_{x2} \\ . \\ . \\ 0_+ \\ 0_- \end{bmatrix} = \sqrt{\frac{2}{n}} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & . & . & \cos(n-1)\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & . & . & \sin(n-1)\alpha \\ 1 & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & . & . & \cos 2(n-1)\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & . & . & \sin 2(n-1)\alpha \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & . & . & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} & . & . & -1/\sqrt{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ . \\ . \\ V_q \\ V_r \end{bmatrix} \quad \ldots(1)$$

Stator Circuit equations:

Voltage Equations:

$$V_{qs} = R_s i_{qs} + \omega_e \Psi_{ds} + p\Psi_{qs} \quad \ldots (2)$$

$$V_{ds} = R_s i_{ds} - \omega_e \Psi_{qs} + p\Psi_{ds} \quad \ldots (3)$$

Flux linkage Equations:

$$\Psi_{qs} = (L_{ls} + L_m) i_{qs} + L_m i_{qr} \quad \ldots (4)$$

$$\Psi_{ds} = (L_{ls} + L_m) i_{ds} + L_m i_{dr} \quad \ldots (5)$$

Current Equations:

$$i_{qs} = \frac{\Psi_{qs}(L_{lr} + L_m) - L_m \Psi_{qr}}{(L_{ls} L_{lr} + L_{ls} L_m + L_{lr} L_m)} \quad \ldots(6)$$

$$i_{ds} = \frac{\Psi_{ds}(L_{lr} + L_m) - L_m \Psi_{dr}}{(L_{ls} L_{lr} + L_{ls} L_m + L_{lr} L_m)} \quad \ldots (7)$$

Rotor circuit Equations:

Voltage Equations:

$$V_{qr} = R_r i_{qr} + (\omega_e - \omega_r)\Psi_{dr} + p\Psi_{qr} \quad \ldots (8)$$

$$V_{dr} = R_r i_{dr} - (\omega_e - \omega_r)\Psi_{qr} + p\Psi_{dr} \quad \ldots (9)$$

Flux linkage Equations:

$$\Psi_{qr} = (L_{lr} + L_m) i_{qr} + L_m i_{qs} \quad \ldots (10)$$

$$\Psi_{dr} = (L_{lr} + L_m) i_{dr} + L_m i_{ds} \quad \ldots (11)$$

Current Equations

$$i_{qr} = \frac{\Psi_{qr}(L_{ls} + L_m) - L_m \Psi_{qs}}{(L_{ls} L_{lr} + L_{ls} L_m + L_{lr} L_m)} \quad \ldots (12)$$

$$i_{dr} = \frac{\Psi_{dr}(L_{ls} + L_m) - L_m \Psi_{ds}}{(L_{ls} L_{lr} + L_{ls} L_m + L_{lr} L_m)} \quad \ldots (13)$$

While indices s, r and l identify the stator, rotor and leakage inductances respectively. V, i, Ψ, L_m, L_s, and L_r denote voltage, current, flux linkage, magnetizing inductance, stator self-inductance and rotor self-inductance respectively.

Where

The torque and speed equation is given with $L_m=(n/2)*M$ and M is symbols R and L stands for resistance and inductance the maximum value of the stator to rotor mutual inductances in the phase variable model. Torque equation is given with

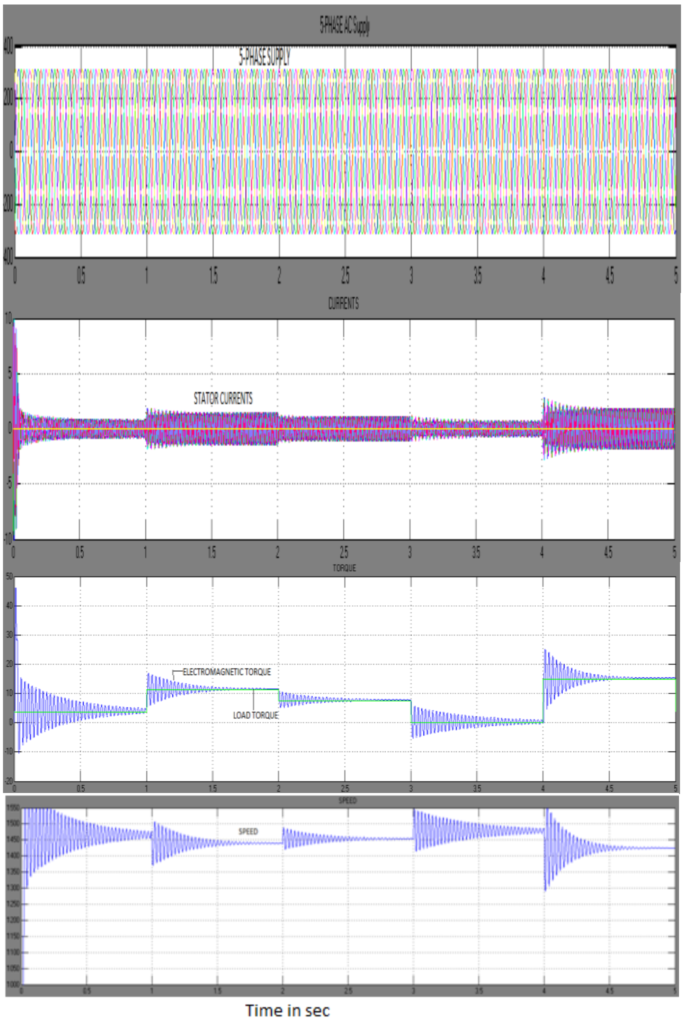
$$Te = PL_m(i_{qs}i_{dr} - i_{ds}i_{qr}) \qquad \dots (14)$$

$$\omega_r = \int \frac{\frac{P}{2}(T_e - T_l) - B\omega_r}{J} dt \qquad \dots (15)$$

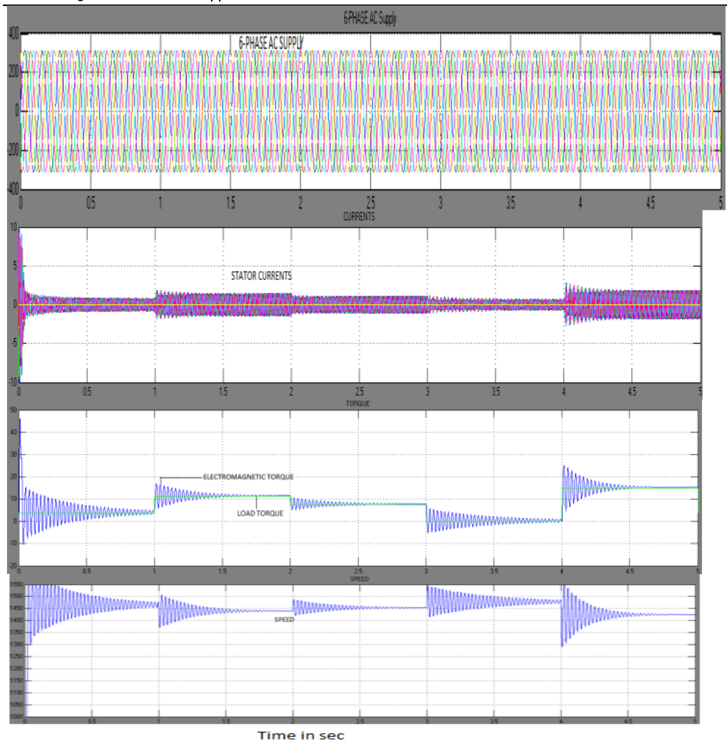
III. SIMULATION RESULTS

The load torque is varying in steps and the corresponding variations in stator current, torque and speed are observed and are shown in Figures show the response of n-phase induction motor. At t=0, motor is 25% loaded and the load is varied in steps as 75%, 50% and 50% at every 1sec respectively. It is seen that the stator current decreases and speed increases with increasing load and the motor torque follows the load torque. Simulation is done for 5, 6, 7, 9, 12, 15 and 18 of High phase induction motors.

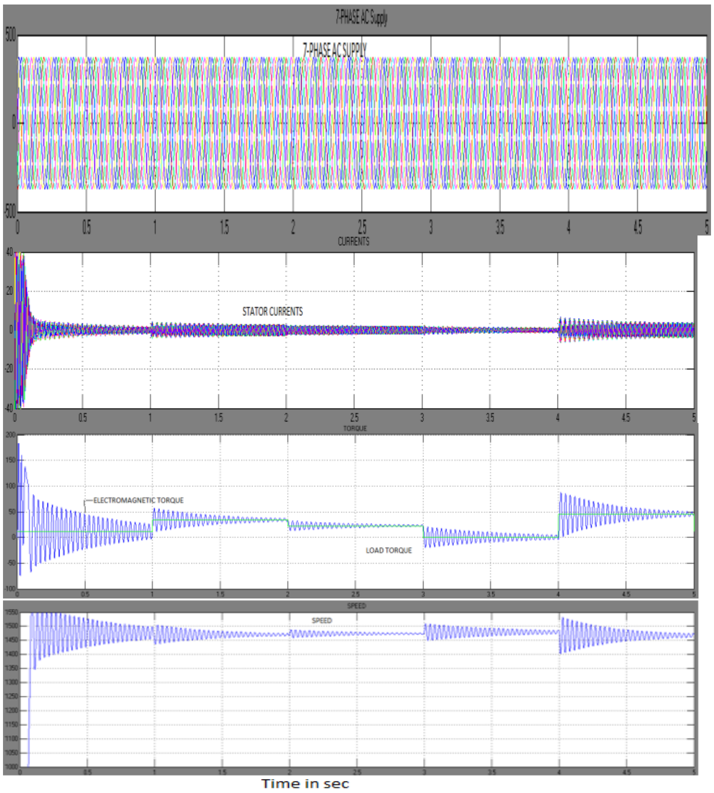
The dynamic response of the Multiphase motors for different loading conditions are observed. The Multiphase induction motor drives develop an electromagnetic torque as 0.25, 0.75, 0.50, no-load and full as that of load applied, the current drawn from the supply varies according to load torque variation and hence the speed of the machine varying inversely with the corresponding load torque. Figs.1 to 2 shows the dynamic response of the HPO Induction motor drive for different phase numbers.



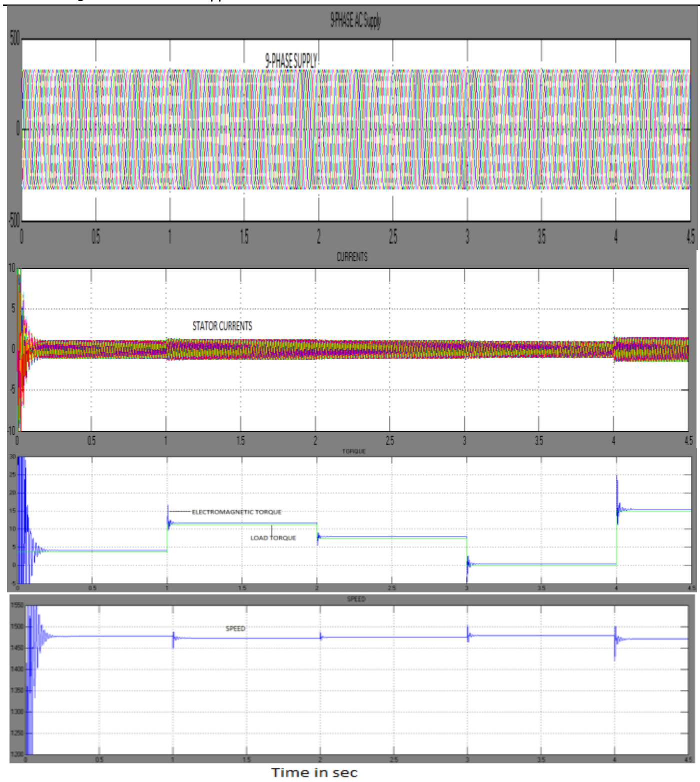
Figs.1 Simulation results of 5 phase induction machine for different loading conditions.



Figs.2 Simulation results of 6 phase induction machine for different loading conditions.



Figs.3 Simulation results of 7 phase induction machine for different loading conditions.



Figs.4Simulation results for 9-phase machine for different load conditions

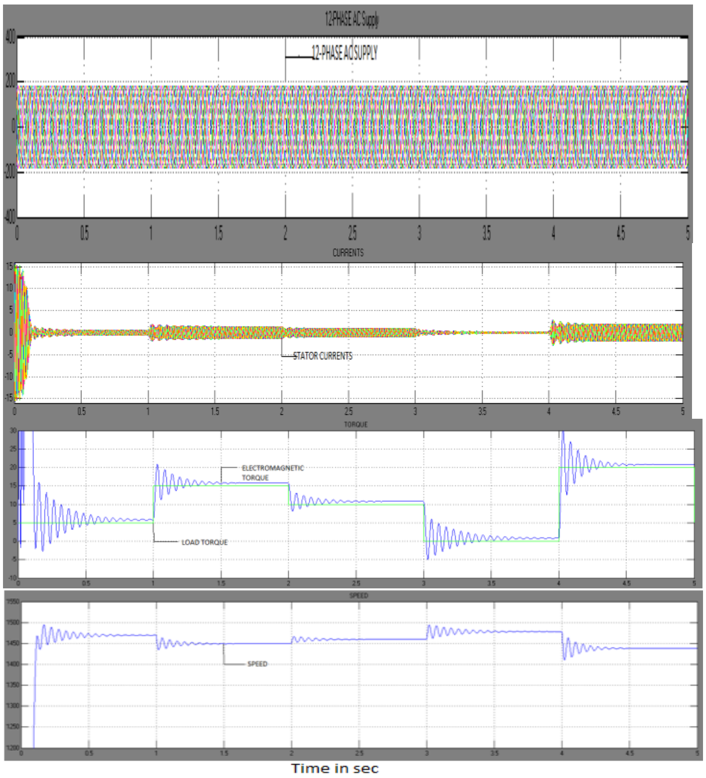
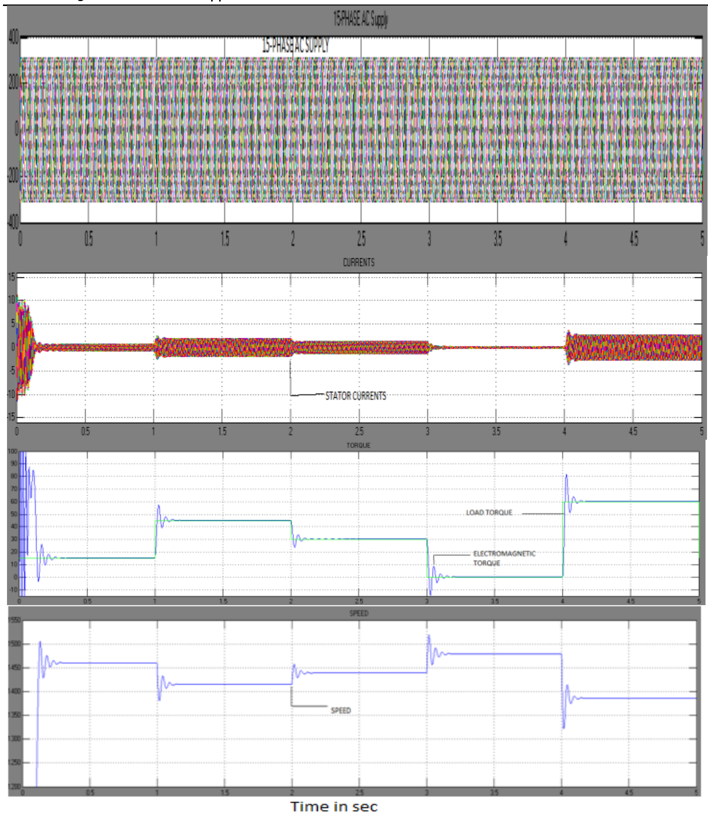
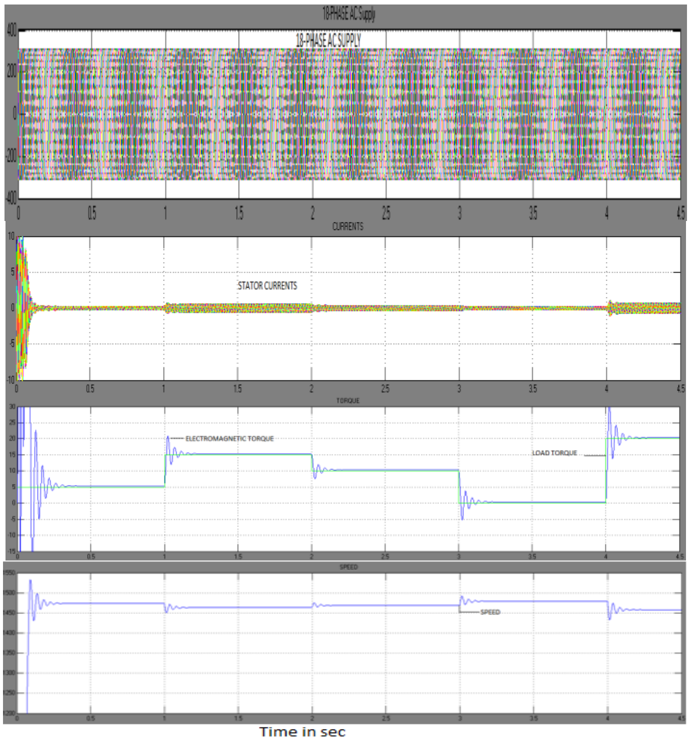


Fig.5.Simulation results for 12-phase machine for different load conditions.



Phase number	Transient time in sec
5	0.15
6	0.5
7	1
9	0.12
12	0.42
15	0.18
18	0.15

Figs.6Simulation results for 15-phase machine for different load conditions.



Figs.7 Simulation results for 18-phase machine for different load conditions

A. *Transient Response*

Figs. 8 to 14 shows the transient response of the Multiphase induction motor drives

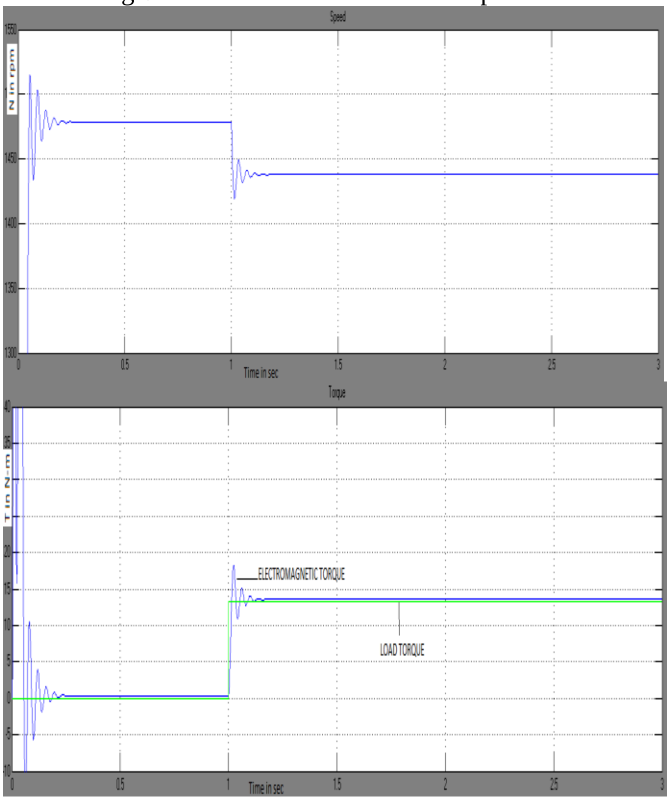


Fig.8. Transient response of 5-phase induction motor for Step load at t=0.15 sec.

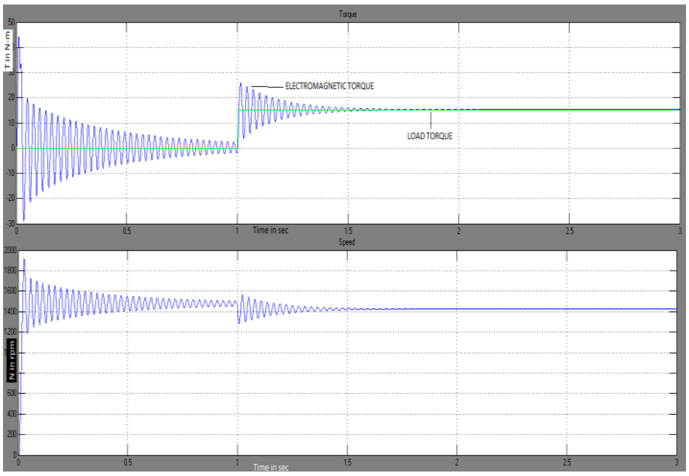


Fig.9.Transient response of 6-phase induction motor for Step load at t=0.5 sec.

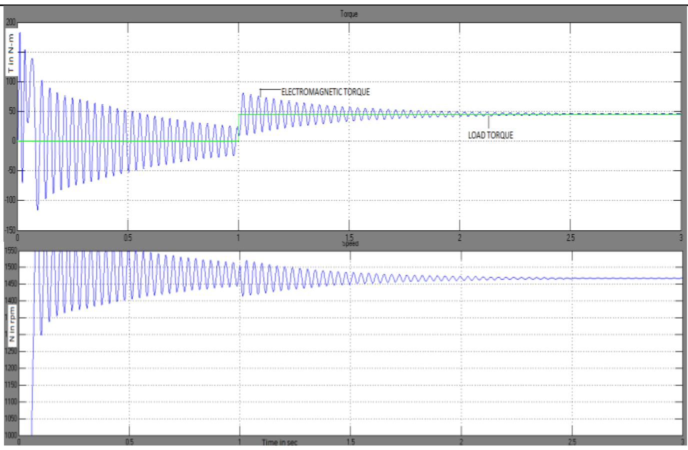


Fig.10.Transient response of 7-phase induction motor for Step load at t=1 sec.

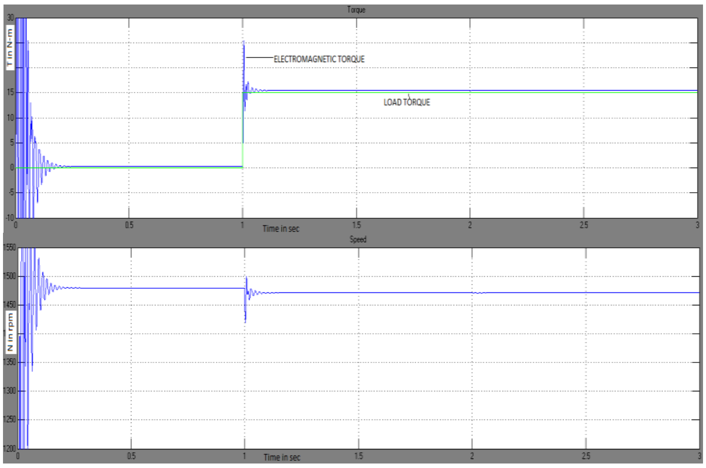


Fig.11.Transient response of 9-phase induction motor for Step load at t=0.12 sec.

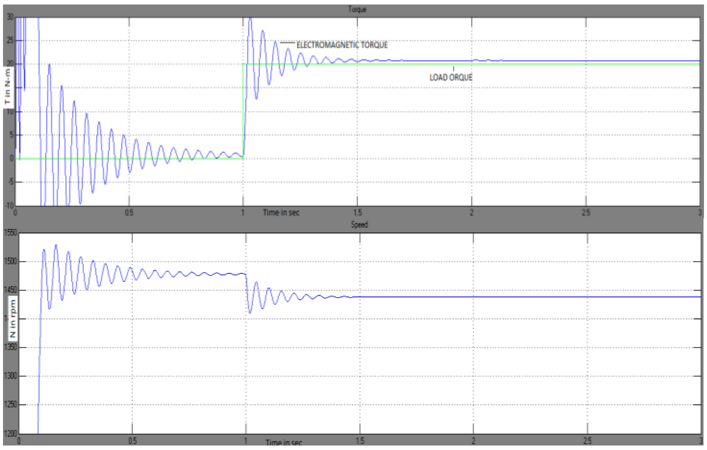


Fig.12.Transient response of 12-phase induction motor for Step load at t=0.42 sec.

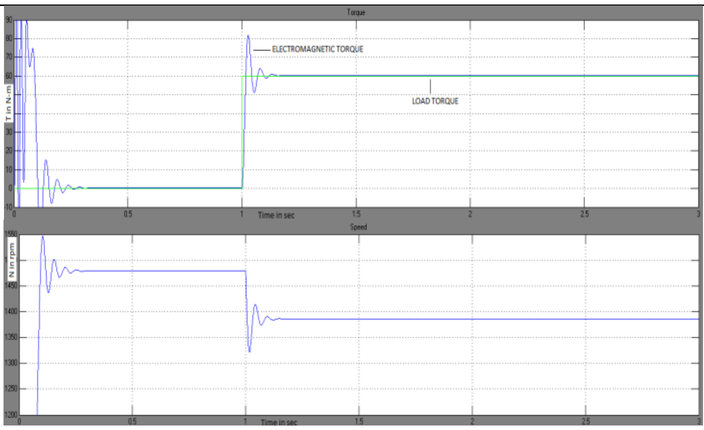


Fig.13.Transient response of 15-phase induction motor for Step load at t=0.18 sec.

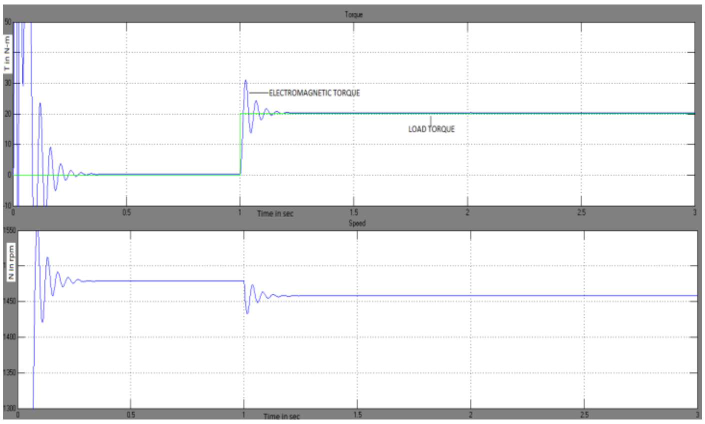


Fig.14.Transient response of 18-phase induction motor for Step load at t=0.15 sec.

IV. SCOPEOF FUTURE WORK

Extension of the investigation of Multiphase systems still has many areas to be accounted for. One of the areas of research is how to control the machine under open phase faults as well as short-circuit turns. The modeling of the machine may be developed using the winding function approach which lead to a controller design, to command the required current to reduce the high phase currents that may occur because of faults.

The modulation strategy using space vector approach is currently attracting the researchers especially on how to utilize the dc link voltage fully in all sectors for Multiphase machine control. The developed Multiphase Induction motor drive may be fed from inverter supply for high power applications. The additional degrees of freedom in Multiphase machine may be used to form a Multi-motor drive system with single inverter supply. This control strategy is restricted to Multiphase machines with sinusoidal flux distribution.

V. CONCLUSIONS

This paper address the generalized model of High phase order Induction machine developed under MATLAB/Simulink. It is developed using the basic built in blocks of Simulink following the corresponding equations. It is tested for different phase number at different loading conditions. The transient response of the model is observed for step change load. In this transient times are observed and tabulated. This model is tested for 18 phase number. The simulation results for phase numbers 5, 6, 7, 9, 12, 15 and 18of generalized HPO Induction machine are presented in this paper. The dynamic and transient results are observed for the fore said phase numbers. The developed model is performing satisfactorily. Here this model is assumed to have symmetrical phase windings and supplied from pure sinusoidal supply. It can be supplied form multiphase Inverter supply and can be analyzed to obtained different parameters.

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